Father of optical trapping awarded a share of the Nobel Prize in Physics

Optical tweezers have endured as an invaluable laboratory tool for manipulating molecules and other small particles.

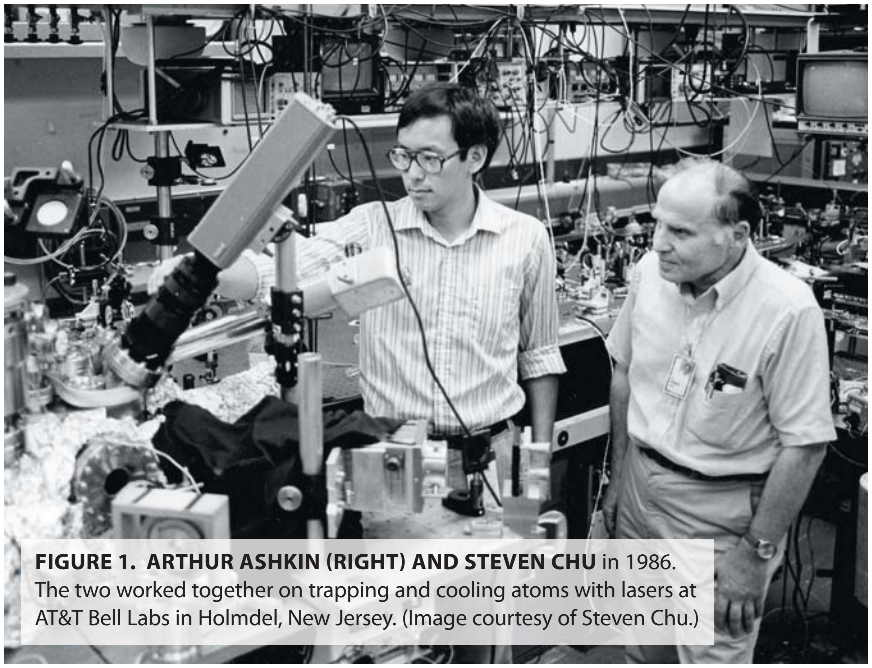

FIGURE 1. ARTHUR ASHKIN (RIGHT) AND STEVEN CHU in 1986. The two worked together on trapping and cooling atoms with lasers at AT&T Bell Labs in Holmdel, New Jersey. (Image courtesy of Steven Chu.)

In 1619 Johannes Kepler proposed that solar radiation pressure, along with solar wind, might explain the observation that a comet's tail always points away from the Sun. His book *De cometis libelli tres* presented the earliest recorded conjecture that light had momentum. Two centuries later James Clerk Maxwell's energy-balance calculations formalized the idea that electromagnetic radiation can indeed exert a force upon a surface. Following the advent of the laser in the 1960s, Arthur Ashkin was one of the first people to explore the possibility of harnessing radiation pressure to manipulate particles with a focused beam of photons.

Only in astronomy, where the net effect of a tiny force could have a large cumulative effect over time, had physicists thought that radiation pressure may be significant. Ashkin, then a researcher at AT&T Bell Labs in Holmdel, New Jersey, wondered whether "one could see observable motion from light pressure forces on particles in the laboratory, using the high intensities of focused laser beams."[1]

That question led him to develop a technique that used a laser to hold and manipulate dielectric particles. Communities of researchers in soft matter, biophysics, atomic physics, and photonics have adopted Ashkin's "optical tweezers" to propel or trap microparticles and to investigate biology at the single-molecule level. Half of the 2018 Nobel Prize in Physics honored Ashkin "for the optical tweezers and their application to biological systems."

"Optical tweezers' greatest influence has been single molecule work in biology," says Stanford University's Steven Chu. Ashkin is shown in figure 1, working with Chu at Bell Labs in the 1980s. "Even though Ashkin himself did not pioneer the first applications in molecular biology, he initiated the ideas." The tool's accessibility has been a boon to its success. Forty-eight years later, optical tweezers still retain their original basic design.

From optical levitation to Stockholm

Ashkin's first demonstration of radiation pressure used the momentum from the light of an upward-pointing 1 W continuous-wave argon laser to levitate a micron-sized latex sphere. Chu says that optical levitation "was motivated by an accidental discovery made while looking at dust particles trapped in a laser beam inside the cavity of an argon laser."

In subsequent experiments, Ashkin used a 150 mW green laser to propel a nonabsorbing polystyrene sphere horizontally in a cuvette of water; in 1969 he found a surprising result. As expected, the incident light exerted a scattering force that accelerated the sphere in the beam's direction. But counterintuitively, the sphere was also drawn toward the higher-intensity center of the beam. Ashkin explained that the surface of the sphere acts as a lens, bending light and thus changing the light's momentum. Conservation of momentum implies that an additional force, called the gradient force, pulls the particle in the direction of more intense light, as shown in figure 2a. Shining a second beam in the opposite direction provided a force that opposed the first beam's scattering force, along the axis, and held the sphere in place. That was the first demonstration of a stable three-dimensional optical trap.[2]

Ashkin calculated that a similar balance of forces could trap not only micron-sized particles but also atoms cooled to near absolute zero.[3] But realizing the dream of trapping neutral atoms with light was still far away. By the late 1970s, Bell Labs management had shut down Ashkin's line of research in atom trapping, leaving him to spend his time on other laser studies. The forces needed to control matter at the atomic scale seemed too small to achieve.

Chu brought a renewed interest in optically trapping neutral atoms when he joined Bell Labs in 1983. He and Ashkin developed a method for cooling atoms before trapping them and found that three pairs of counterpropagating laser beams intersected in a region that acted like a viscous soup.[4] In that "optical molasses," a cloud of atoms was cooled to a record 240 μK. As Kishan Dholakia of the University of St Andrews says, that was akin to slowing "the speed of a jet plane down to a crawl." Viscous confinement and cooling later won Chu a share of the 1997 Nobel Prize in Physics (see PHYSICS TODAY, December 1997, page 17) and gave Ashkin insight into a robust optical trap design.

Ashkin's atom-trapping proposal[3] emphasized an optical trap that had a large volume, but suggested that a single, tightly focused Gaussian beam could also serve as a trap. In his earlier work on a particle in an unfocused beam, incoming rays scatter away from the beam's axis and give the particle forward momentum. But for a tightly focused beam, shown in figure 2b, incoming light rays converge as they approach the particle. The scattering rays make a smaller angle with the beam's axis. To conserve momentum, the particle must gain a component of backward momentum. The net gradient force gets contributions, some forward and some backward, from all the rays in the beam. For some position along the axis, the sum of the scattering and gradient forces is zero and the particle is trapped—held in place by optical tweezers.

Until the invention of optical molasses, neither atom trapping nor single-beam optical trapping had been considered practical. Optical molasses created ultracold atoms at a density of 10^6 cm^{-3}. Ashkin and his Bell Labs colleagues found that a single Gaussian beam focused on a cooled cloud of atoms could trap the atoms that randomly wander into the trapping volume. The trap collected 500 atoms at a density of 10^{11} cm^{-3}. Ashkin then proposed trapping a micron-sized polystyrene sphere in water and relying on radiation pressure forces to hold it. He went on to trap and manipulate silica particles as small as 25 nm. Says Chu, "I remember vividly the look on his face when he said 'Look, we can hold onto this!'" Ashkin's optical tweezer design, described in his 1986 paper,[5] has remained unchanged for decades.

A biological explosion

After finding that optical tweezers could handle particles of different shapes, Ashkin used them to trap rod-shaped tobacco mosaic virus. After leaving out a test tube containing the virus suspended in water overnight, he noticed the appearance of "strange new particles, that were apparently self-propelled."[6] He called the particles "bugs." Ashkin found himself with a tube full of bacteria.

That experiment led to Ashkin's discovery that optical tweezers could capture and move a bacterium without damaging the organism. The 515 nm green argon laser he initially used killed the bacterium. The cell burst as it absorbed the light, in a process Ashkin dubbed "opticution." Switching to a 1064 nm IR neodymium-doped yttrium aluminum garnet laser, to which most biological materials are transparent, solved the problem.[7] Ashkin trapped *Escherichia coli* bacteria and yeast cells for hours and observed cell reproduction.

Days after reading about Ashkin's feat, Steven Block, a biophysicist at Stanford, had built his own optical trap. He and his team later published the first quantitative measurement of a biological system using optical tweezers.[8] His team trapped a single, spinning *E. coli* bacterium tethered by its flagellum to a glass surface and measured the torsional flexibility of the nanoscale hook component at the bacterium's base, which couples the flagellum to the bacterial flagellar motor.

Smaller and smaller

Optical tweezers work best when the trapped particle has dimensions similar to the size of the trap itself. A laser beam can be focused down to a spot the size of the laser wavelength. The laser intensity needed to manipulate the particle scales with the square root of the particle's volume.

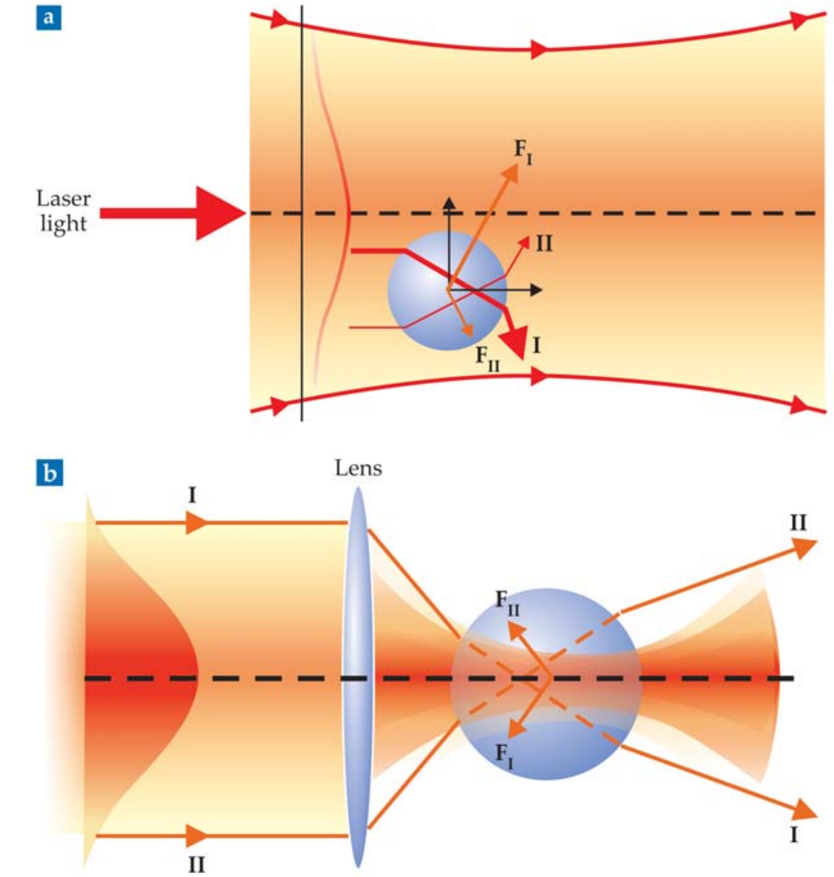

FIGURE 2. OPTICAL TWEEZER DESIGN. (a) When a laser beam strikes a dielectric sphere, most of the light is refracted. Refracted rays I and II give rise to forces $\mathbf{F}_I$ and $\mathbf{F}_{II}$ that act on the particle in the direction opposite the momentum change. Because the beam is most intense toward its center, as depicted by the sideways red curves, ray I is more intense than ray II and the sphere is drawn toward the beam axis. The net force can be separated into gradient and scattering components. (Adapted from ref. 1.) **(b)** In a single-beam optical tweezer, a highly focused beam leads to an axial force that points toward the focal point. Forces $\mathbf{F}_I$ and $\mathbf{F}_{II}$ arise from refracted rays I and II but push the particle toward the focal point. For a strong enough focus, the net gradient force exceeds the scattering force, trapping the particle very near the focal point. (Adapted from ref. 4.)

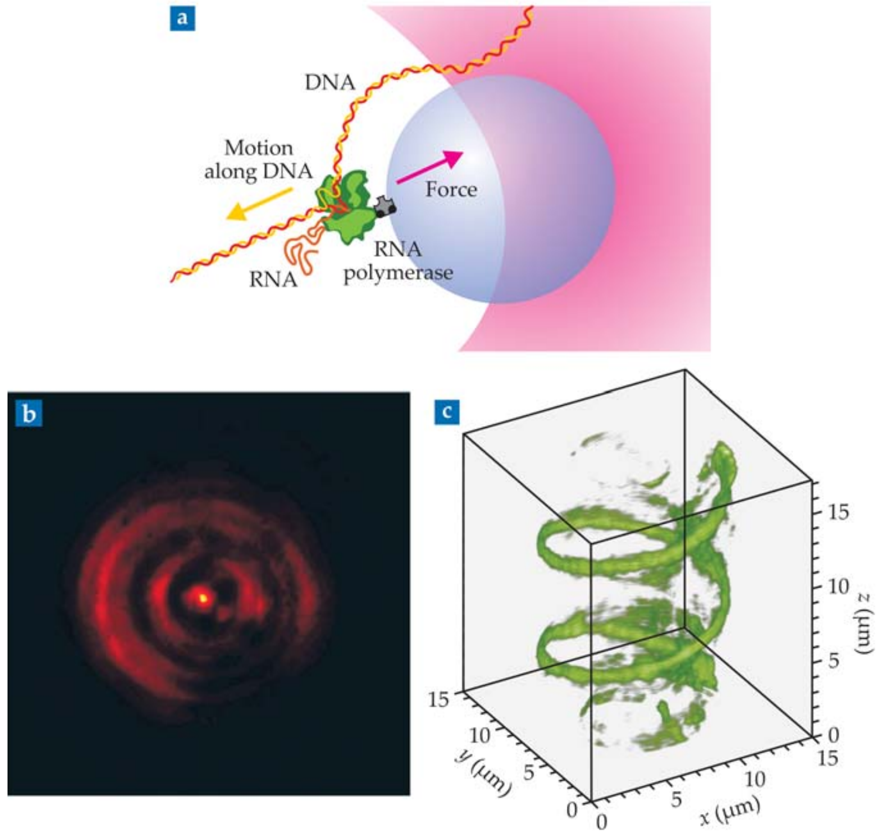

FIGURE 3. OPTICAL TWEEZER TOOLBOX. (a) An RNA polymerase enzyme (green) synthesizes a strand of RNA (orange) from DNA. The enzyme is fixed to a micron-sized polystyrene sphere. Optical tweezers (pink) hold the sphere with a force of known magnitude. The force exerted by the enzyme's movement can be measured as the enzyme transcribes the genetic material. (Image courtesy of Steven Block.) **(b)** A calcium carbonate particle in a vacuum scatters light while rotating at 10 MHz in an optical trap. (Image courtesy of Kishan Dholakia.) **(c)** A working tractor beam maintains the same spiral intensity distribution (green) from the bottom of the image upward. Particles trapped by the spiral are forced upstream by radiation pressure. (Image courtesy of David Grier.)

Still, biological systems rely on nanometer-scale macromolecules, which are much smaller than available laser wavelengths. For example, nanometer kinesin motor proteins walk along microtubules and ferry cargo within cells. Using a technique developed at Stanford, Block attached motor molecules to larger micron-sized polystyrene sphere "handles." To infer the protein's actions, he grasped a sphere in optical tweezers and observed the sphere as the protein stepped along a microtubule. "If a tiny ant grabs a potato chip, you only know the ant's there because you can see the chip moving," he says.

In 1993 Block's team published the first measurements of the size of a step taken by a motor protein. Optical tweezers were the perfect tool because the radiation force of a few-milliwatt laser matched the forces produced by the proteins. Block's work prompted Ashkin and other researchers to ask if it might be possible to measure the steps taken by the enzyme RNA polymerase as it transcribes a DNA template. Block's team set the record for single-protein measurement sensitivity and found that RNA polymerase moves in 3.4 Å steps, the exact spacing of DNA base pairs (see figure 3a).

Michael Berns at the University of California, Irvine, challenged his electrical engineering students in 1989 to see who could be first to build optical tweezers from components in the lab. He got a call at 3am saying "We did it!" and went on to create optical tweezers for manipulating organelles inside of cells. He and his colleagues used a 130 mW laser to move a chromosome inside a cell without damaging the cell membrane.[9] The researchers developed fundamental microsurgery in which a cell is perforated with pulsed laser "scissors" and materials in the cells are manipulated—for example, sections of chromosomes are removed or replaced.

The future is nonlinear

New techniques based on shaped beams of light and multiple simultaneous traps have extended the realm of what optical tweezers can achieve. In 1994 Jeffrey Finer, James Spudich, and colleagues at Stanford stretched an actin filament using two optical traps. Measuring the displacement caused by a myosin motor protein as it walked along the filament gave the researchers insight to the forces that underlie muscle contraction. (For more investigations of single biomolecules using optical tweezers, see the article by Terence Strick and colleagues, PHYSICS TODAY, October 2001, page 46.)

Deflectors and mirrors can split a single beam of light into many, each of which may be treated as separate optical tweezers. The advent of spatial light modulators, which are used in many digital projectors, allowed David Grier, now at New York University, to go even further and manipulate multiple particles in a reconfigurable hologram. "You type one line of code, and you get a pattern of traps," he says. A particle can become trapped at the bright regions of any holographic image. Rapidly projecting a sequence of images will move trapped particles in arbitrary trajectories.

Optical tweezers have found their way into the Guinness Book of World Records. Using a circularly polarized laser beam, Dholakia and colleagues created the world's smallest gyroscope by trapping a 4 µm calcium carbonate particle in a vacuum. The change in polarization of the light as it passed through the particle exerted a torque on the particle. The lack of friction in the vacuum resulted in a rotation rate of 10 million revolutions per second (see figure 3b), a record for a manmade spinning object. Similar experiments could provide insight into how friction works in very small systems, which has relevance to microscopic device development.

The possibilities for manipulating particles with different patterns of light are endless (see, for example, PHYSICS TODAY, April 2013, page 20). Grier says that using a coiled pattern of light, shown in figure 3c, can even pull particles in an upstream direction along the coil's entire length: "That's a real-life tractor beam."

About the laureate

Arthur Ashkin was born in 1922 in Brooklyn, New York. In 1952 he earned his PhD from Cornell University. His thesis adviser, Sidney Millman, recommended that Ashkin work for Bell Labs. Ashkin had a 40-year career in laser research there, and he holds 47 patents. He is a fellow of the Optical Society, the American Physical Society, and IEEE. He now works in his home lab in New Jersey. At age 96 he is the oldest person to receive a Nobel prize.

Rachel Berkowitz

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